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METHODOLOGY

Occupational health impacts: offshore crane lifts in life cycle assessment

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Abstract
Background, Aim, and Scope The identification and assessment of environmental tradeoffs is a strongpoint of life cycle assessment (LCA). A tradeoff made in many product systems is the exchange of potential for occupational accidents with the additional use of energy and materials. Net benefits of safety measures with respect to human health are best illustrated if the consequences avoided and health impacts induced by additional emissions are assessed using commensurable metrics. Our aim is to develop a human health impact indicator for offshore crane lifts. Crane lifts are a major cause of accidents on offshore oil and gas (O & G) rigs, and health impacts from crane lift accidents should be included in comparative LCA of O & G technologies if the alternatives differ in the use of crane lifts.
Materials and methods Accident records for mobile offshore petroleum installations were used to develop an empirical occupational health indicator for crane lifts in LCA. Probabilistic parameters were introduced in the procedure, and results were calculated by Monte Carlo simulation. The disability adjusted life years (DALY) framework was used to classify health outcome. The characterization factor for offshore crane lifts was applied in three comparisons to evaluate the significance of crane lifts to human health impacts from drilling technology.
Results The mean occupational health impact per crane lift was $4.5 \cdot 10^{-6}$ DALY, with cumulative percentiles $\{P_{2.5}, P_{50}, P_{97.5}\} = \{6.0 \cdot 10^{-7}, 3.1 \cdot 10^{-6}, 1.7 \cdot 10^{-5}\}$. Analogously, the fatal accident frequency was described by $\{P_{2.5}, P_{50}, P_{97.5}\} = \{7.6 \cdot 10^{-9}, 3.9 \cdot 10^{-8}, 2.0 \cdot 10^{-7}\}$, with mean $5.6 \cdot 10^{-8}$ lives lost per crane lift.
Discussion The uncertainty in the results is caused mainly by the random nature of accidents, i.e., variability in accident frequency. Applications of the characterization factor indicate that although crane lifts may not be significant to the overall health impact of the life cycle of drilling fluids, they are important to the occupational safety of employees on offshore drilling rigs and contribute significantly to the life cycle health impact of loading technologies used to transport drilling waste to shore. A comparative LCA of technologies for loading and offloading drilling wastes shows that a recently developed hydraulic system performs better than the traditional crane lift alternative in terms of human health impacts.
Conclusions With the availability of statistics to assess the risk of single mechanical operations, safety aspects may well be included in LCA. For the case of offshore crane lifts, the uncertainty in the characterization factor compares favorably to what is indicated for other human health impact chains. In further work of quantifying occupational health impacts in DALY using accident statistics, it is advised to see if records of non-recoverable injuries (fatalities and amputation cases) can be used to simplify the damage assessment procedure as recoverable injuries were insignificant to the total burden from crane accidents.
Recommendations and perspectives The characterization factor for crane lifts identifies contributions to life cycle health impact from loading technologies that otherwise would have been overlooked in LCA. While many contest the inclusion of occupational accidents in LCA, our results

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show that such impacts can be included and that their consideration adds valuable insights.

Keywords Crane lifts · Disability adjusted life years · Fatal accident rate (FAR) · Fatality · Health · Injury · LCIA · Life cycle impact assessment · Monte Carlo · Risk · Working environment

1 Background, aim, and scope

This paper is part of an effort to use life cycle assessment (LCA) in the evaluation and selection of drilling fluid chemicals and drilling waste technology. Drilling fluids are used in oil and gas (O & G) drilling operations to move rock carvings out of the well, stabilize well walls, and cool and lubricate the drill bit. Fluid composition at any drill site varies according to geology, availability of supporting technology, and prevailing regulations concerning the use of chemicals and treatment of drilling wastes. The present focus of regulations is directed towards impacts at the drill site or in relation to the treatment of waste. There is a growing understanding that environmental interventions occur throughout the life cycle of drilling fluids and that an overall evaluation of drilling technology must include a life cycle perspective that encompasses production and use of fluids as well as waste logistics and drilling waste treatment technologies. The large variation in drilling fluid system designs and complementary environmental issues calls for the use of a holistic tool to assess drilling technologies—such as offered by LCA.

Two aspects have emerged as especially important in the regulation of offshore O & G activities in the North Sea: ecotoxic impacts from planned and accidental spills and the safety of the offshore workforce. Both aspects have to be treated within the framework of LCA if it is to be used by offshore operators in communication with external stakeholders. The subject that we discuss here is the issue of safety and the assessment of accidents with human health impacts. Other environmental issues in the life cycle of drilling fluid technology are discussed by Pettersen (2007).

Mechanical lift operations cause a large fraction of accidents on offshore O & G units. In the UK North Sea, they constitute 25% and 40% of all reported incidents, and 50% and 68% of incidents with person injuries on fixed and mobile units respectively (DNV 2005a, b). Hence, crane lifts are a major driver for accidents in the offshore O & G industry. Our aim is to include health impacts from crane lifts in LCA by development and application of a characterization factor for the health impacts caused by crane lift accidents.

The source data originates from the North Sea area and results are principally to be used in the context of offshore O & G activities with similar technology designs. Results are applicable also in risk assessment of offshore processes since the methodology that we apply draws on the methods of this field.

The significance of crane lifts to occupational health is illustrated through three applications. First, health impacts occurring from crane lifts are compared to the total occupational health burden offshore; second, crane lifts are compared with human health impacts from other unit processes in the drilling fluid life cycle; and third, a comparative assessment is performed of technology alternatives for loading of drill cuttings aboard a service vessel.

2 Materials and methods

2.1 Occupational health in LCA

In a summary of the efforts made to include work environment in LCA, Poulsen and Jensen (2004) recommend that the practitioner select the method depending on the goal and scope of the assessment. Working environment may be incorporated into the conventional life cycle assessment framework, or it may be discussed separately within a life cycle approach. The latter approach is taken by Schmidt et al. (2004a), who complement LCA of house insulation materials with an assessment of occupational health aspects.

If the purpose of the assessment is to quantify tradeoffs introduced by technology differences, it is our view that occupational impacts should be integrated to LCA and presented in metrics preferably commensurable to other health impacts in the life cycle. For instance, reduction in crane accidents can be realized through better safety management. Still, principally it is achieved by replacing cranes with other means of loading of cargo. In order to assess the performance of alternative technologies, impact chains that share endpoints, such as human health impacts both internal and external to the process, should share endpoint category indicator. A framework to achieve this is offered by the disability adjusted life years (DALY). Developed for the World Bank and the World Health Organization and originally designed for health economics (Murray and Lopez 1996), the DALY concept has been used for various impact chains in life cycle impact assessment (LCIA). Human health impact chains assessed with DALY include toxicity (Hofstetter 1998; Goedkoop et al. 1998; Crettaz et al. 2002; Pennington et al. 2002; Huijbregts et al. 2005; Meijer et al. 2005), ionizing radiation (Frischknecht et al. 2000), and road noise (Müller-Wenk 2004), as well as occupational health impacts in the US input–output (I/O) table (Hofstetter and Norris 2003).

Occupational health impacts may be included in LCIA by relating records of fatalities, injuries and illnesses to product outputs from sectors or single companies (Hauschild and Wenzel 1998; Poulsen and Jensen 2004). Occupational health impacts may be quantified as direct impacts occurring within the sector or company (e.g., Antonsson and Carlsson 1995; Hauschild and Wenzel 1998; Schmidt et al. 2004b) or including repercussions in the whole economy (Hofstetter and Norris 2003). The latter approach requires combination with an I/O model. Hybrid-LCA accommodates the combination of traditional process-based LCA with I/O models (Heijungs and Suh 2002).

Impact category indicators based on sector data may be established relatively easily. However, comparative LCAs require health impacts on unit process level for the foreground system. The detail with which the offshore O & G industry reports accidents allows establishment of a quantitative relationship between unit processes and injury characteristics such as frequency and health consequence. In this work, we use data reported for the O & G industry to develop an empirical characterization factor for the human health impacts from crane lifts with indicators modeled in units of DALY per crane lift.

2.2 Outline of method

The UK Health and Safety Executive has compiled incident records for floating and fixed offshore petroleum units on the UK continental shelf for the period 1980–2003 (DNV 2005a, b). Data for floating (i.e., mobile) units were selected in this work as mobile units normally are employed when drilling in new areas. Every incident is recorded with year, rig type, mode of operation, number of people injured, and a brief description of the event. The database of 3,105 incidents, of which 817 resulted in person injury, is the most complete compilation of offshore accident records for the period. Unfortunately, the classification of accidents in the database groups all incidents from lifting operations into the class of crane lift incidents. Separation between accidents related to lifts performed with cranes and lifts performed with other equipment, such as the drilling derrick or draw works, must, therefore, be done before the data can be used to quantify the impacts caused by crane lifts.

We define injury events as accidental incidents with consequences to the health of personnel. According to the database compiled by DNV (2005a), there were 588 incidents which resulted in injury to personnel on floating (i.e., mobile) units in the period 1980–2003. Of these, 399 are classified as caused by or involving lifting equipment. Our focus was injuries caused by crane lifts, so the cases involving derrick operations and draw works were excluded based on the description of events given in the accident records. This resulted in a set of 165 cases of crane lifts causing injury to personnel. Text searches in the cases classified as having zero personnel injuries identified 12 additional cases. The end set consisted therefore of 177 cases from the period 1980–2003. These are hereafter referred to as crane lift injury events (CIE) and form the basis for exposure and effect assessment.

The source data reports accident frequency per rig year. In order to establish the frequency of accidents with personnel injuries per crane lift, a connection has to be made between accident frequency and stressor activity. The stressor that we consider in this case is one single crane lift. The relationship is established by estimation of the average annual number of lifts made on a subset of offshore rigs. Homogeneity in the source data was ensured by restricting it to a single type of mode of action within a select group of rig types and to the period 1990–2003. Exposure assessment, therefore, was based on semi-submersible (SS) and jack-up (JU) rigs in drilling mode. The drilling operation is a fairly generic mode of operation, and SS and JU rigs are similar in that they both are mobile and are predominantly used in drilling operations. Together, SS and JU rigs represent the bulk of rigs used in exploration drilling in UK waters.

There is no formal procedure for impact assessment in LCA. However, there is a requirement for the establishment of a cause–consequence model that relates inventory items with safeguard objects. Cause–consequence models in LCA are often based on the structure of environmental risk assessment in that a separation is made between exposure and effect assessment and complemented by damage assessment if endpoint indicators are used. The literature defines a generic cause–consequence model as follows (Hertwich and Hammitt 2001; Udo de Haes and Lindeijer 2002):

> Stressor–Insult–Stress–Consequence–Value lost
> Analogously, for offshore crane lifts the following chain of events is defined:
>
> Crane lift–Incident–Injury event (CIE)–Injury type(s)–(DALY)

Within this framework, exposure assessment is the estimation of stress as a result of stressor activity, calculated as injury events per crane lift. Effect assessment is the translation of stress to consequence, interpreted here as the distribution of injury and fatality per injury event. Health consequences are further aggregated into value lost by use of the DALY concept.

While source data variability is a problem in exposure assessment, it is a source of validity in accident outcome compilation. To achieve data that is representative of the outcome of crane lift accidents, all crane lift accidents recorded in the period 1980–2003 were used in the effect

assessment. Although limited to crane lifts, the data encompasses all rig types and modes of operation. The framework of Murray and Lopez (1996) was used in the damage assessment. Age weighting and discounting of life years was not performed.

Judging from the volume of applications, Monte Carlo analysis is becoming the norm when accounting for uncertainty in life cycle inventory and impact assessment (see, e.g., Hertwich et al. (2000); Huijbregts (2002); Ciroth et al. (2004); Geisler et al. (2005)). Monte Carlo simulation is used also in the work presented here. All parameters are treated as independent distributions with the exception of the duration for recoverable injuries and the disability weight of accident outcomes—both predefined single values in the DALY framework.

The next sections describe the impact assessment procedure in detail. Results and applications are presented in Section 3.

2.3 Exposure assessment

A homogenous dataset helps reduce uncertainty in the exposure assessment. We selected SS and JU rigs for the exposure assessment as they have similar activity profiles and represent the main share of crane lift accidents. Both are employed in drilling operations and perform a large number of crane lifts per hour. Crane lift injury events on SS and JU units were extracted from the dataset and combined with years of active drilling on SS and JU rigs. Drilling years were calculated for UK waters using data from RigPoint (ODS-Petrodata 2005). A log-normal distribution was fitted to the frequency of injury events per drilling year in the period 1990–2003, as illustrated in Fig. 1. The result is a distribution for the number of CIE per year of active drilling.

Normalization to CIE per crane lifts was achieved by estimating the number of lifts performed per hour. Crane lift intensity on the rig varies greatly, from zero lifts per hour in quiet periods to peaks of up to 50 during loading of supplies. On average, approximately eight to ten crane lifts are performed per hour (Eikill GO, Statoil ASA, personal communication). This is within the interval reported for crane lift intensity on fixed installations by Safetec (2005). Taking into considerations that the intensities average out over one rig year, a log-normal distribution with a mean of 9 and a 99th percentile of 25 was assumed. Values >30 crane lifts per hour were removed from the set. This gives a quite wide distribution, equivalent to our uncertainty in the average crane lift intensity.

Equations used in the assessment procedure are listed in Table 1. Note that equation 1 is balanced for 8,760 h per year. Parameters used in Monte Carlo simulations are listed in Table 2.

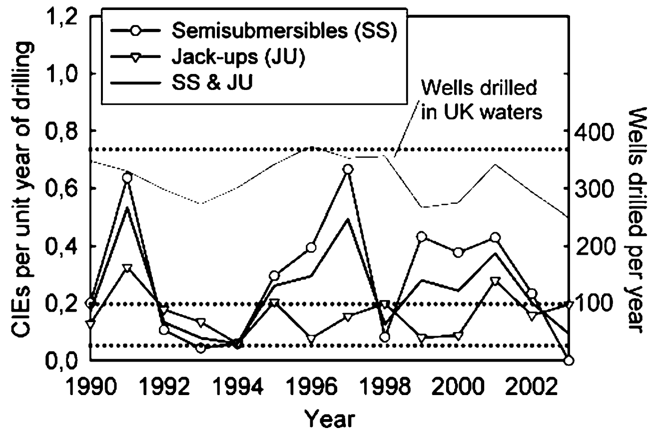

Fig. 1 Injury events per unit year for jack-ups (*JU*) and semi-submersible (*SS*) drilling rigs. *Dotted lines* indicate the geometric mean and boundaries of the interval of 95% confidence for the distribution fitted to the aggregated scores for JU and SS rigs. The large increase of reported injury events in 1997 is thought to be an artifact of the introduction of the RIDDOR95 reporting scheme in April 1996. Drilling activity figures are from the UK Department of Trade and Industry (http://www.dti.gov.uk/) and include all well and unit types

2.4 Effect and damage assessment

Health outcomes found in the 177 CIEs were classified based on the description of events. The result is presented in Table 3. Equations used in the effect and damage assessment are listed in Table 1; i.e., Eqs. 2 and 3. Remaining parameters for the Monte Carlo simulation are given in Table 2. Disability weights and durations for the recoverable injuries were modeled as defined parameters; i.e., set constant.

Given its expected influence on the end result, we find it necessary to discuss the remaining lifetime separately. A program initiated by the Norwegian Oil Industry Association (OLF; http://www.olf.no/arbeidsliv/aldringoghelse/) investigated the age distribution of the Norwegian offshore workforce. Average age was between 45–50 years for the various operators, and one of the operators (Norsk Hydro) reported a female representation of about 20%. Several studies have reported higher accident rates among young employees offshore compared to more experienced employees (e.g. Forbes 1997; Mueller et al. 1987). In order to include this aspect, the age distribution reported by Forbes (1997) for the age at injury was preferred over an age distribution of the entire workforce reported by, e.g., OLF. The age distribution was combined with life tables for males in the UK reported by GAD (2006) for 2002. The result is an average remaining lifetime at the time of the accident of 47 years, with standard deviation 6.1 years. Male life expectancy was used in the simulations from the observation that all cases found in the production of Table 3 that specified gender, indicated male victims.

Table 1 Equations used to assess exposure, effect and health damage

Equation	Metric
1 $F = \frac{u}{8760c}$	CIE per crane lift
2 $E_i = \frac{n_i}{n_t} = \frac{n_i}{177}$	Outcome i per CIE
3 $D = \sum_i (E_i d_i w_i)$	DALY per CIE
4 $Q = F \cdot D = \frac{u}{8760c} \frac{1}{n_t} \sum_i (n_i d_i w_i)$	DALY per crane lift

i Health outcome of type i (see Table 3 for list), *F* number of cases of injury to human health per crane lift, *u* CIE per year of drilling, *c* crane lifts per hour (8,760 h per year), E_i number of health outcomes of type i per CIE (i.e., effect factor for health outcome i), n_t total number of CIE=177, n_i number of health outcomes of type i in the total set of CIE, *D* DALY per CIE (i.e., damage factor for health outcome i), d_i duration of health outcome i, w_i disability weight for health outcome i, *Q* damage to human health per crane lift, *CIE* crane lift injury event, *DALY* disability adjusted life years

3 Results and discussions

3.1 Injury events per crane lift

In order to calculate the number of injury events per crane lift, 200,000 Monte Carlo simulations of Eq. 1 in Table 1 were performed according to the distributions listed in Table 2. Mean value of the resulting distribution is $3.9 \cdot 10^{-6}$ injury events per crane lift with cumulative percentiles $\{P_{2.5}, P_{50}, P_{97.5}\} = \{5.5 \cdot 10^{-7}, 2.8 \cdot 10^{-6}, 1.4 \cdot 10^{-5}\}$.

Knowing that approximately 90% of the CIEs indicate falling objects as the secondary cause to the accident, we conclude that the injury rate from falling objects per lift (i.e. dropped load) estimated in this work fits well with the frequency of dropped load used in risk assessment in offshore engineering, e.g., $2 \cdot 10^{-5}$ dropped objects per lift indicated by Mazzola (2000). Some discrepancy is expected between these two results as the rate found here includes crane lifts only while previous estimates have been based on accidents caused by all types of lifting equipment. In addition, the factor quantified here only includes incidents with injuries to personnel.

Table 2 Parameters in Monte Carlo simulation

Parameter	Distribution[a]
u	L[ξ, φ]=[−1.62, 0.67][a]
c	L[ξ, φ]=[2.1, 0.50][b]
n_t	177
n_i	U[Certain cases, certain cases + potential cases]
d_{lifelong}	N[μ, σ]=[47.0, 6.1]
d_{fracture}	As listed by Murray and Lopez (1996, Annex Table 3)
d_{minor}	0.024[c]

L Log-normal distribution, *U* uniform distribution, *N* normal distribution
[a] Fitted to CIE frequencies for semi-submersible and jack-up rigs in the period 1990–2003. Values are in natural log-scale
[b] Values are in natural log-scale (lifts per hour)
[c] The recovery period specified by Murray and Lopez (1996, Annex Table 3) for open wounds

Table 3 Injuries found in 177 crane lift injury events

Health outcome [i]	Cases[a] [n_i]	Weight[b] [w_i]
Fatalities	2 (+2)	1.000
Amputation–thumb	1 (+1)	0.165
Amputation–finger	4 (+5)	0.102
Amputation–toe	0 (+2)	0.078
Amputation–foot	1 (+0)	0.300
Fracture–face bones	0 (+4)	0.223
Fracture–rib or sternum	0 (+3)	0.199
Fracture–pelvis	1 (+2)	0.247
Fracture–clavicle, scapula, or humerus	1 (+1)	0.153
Fracture–radius or ulna	1 (+2)	0.180
Fracture–hand bones	9 (+16)	0.100
Fracture–patella, tibia, or fibula	3 (+8)	0.271
Fracture–ankle	1 (+4)	0.196
Fracture–foot bones	1 (+14)	0.077
Minor injuries	88 (+64)[c]	0.108[d]

[a] On format: certain cases (+potential cases)
[b] Disability weights from Murray and Lopez (1996, Table 4.4)
[c] Modeled so that $\Sigma(n_i)|_i = n_t = 177$
[d] Assumed with equal weight to open wounds

Sample correlation coefficients were calculated according to Morgan and Henrion (1990, p 208) for the contribution to injury event frequency from CIEs per unit per year (u, 0.74) and crane lifts per year (8,760·c, −0.42). The results show that the uncertainty in the results is dominated by the random nature of accidents (variability in u) and not uncertainty in the estimation parameter c.

3.2 Health impact per injury event

Disability adjusted life years per injury event was calculated by 200,000 Monte Carlo simulations of equation 3 in Table 1. Years lost due to premature death and disability adjusted life years from amputations are illustrated in Fig. 2. The average contribution from mortality is 69.1% of the total burden, while amputation cases on average account for 30.5% of the total burden from crane accidents. This leaves 0.4% for the fracture cases and minor injuries together. The result corresponds with the findings of Hofstetter and Norris (2003) who concluded that about two thirds of the burden of disease from occupational injuries in the economy is due to fatalities. For the case of health impacts from crane lifts, the remaining one third is represented by lifelong injuries. This is not unexpected given the duration of the lifelong injuries compared to the recoverable injuries.

Discounting would reduce the importance of lifelong injuries for the burden per crane lift. In further work of

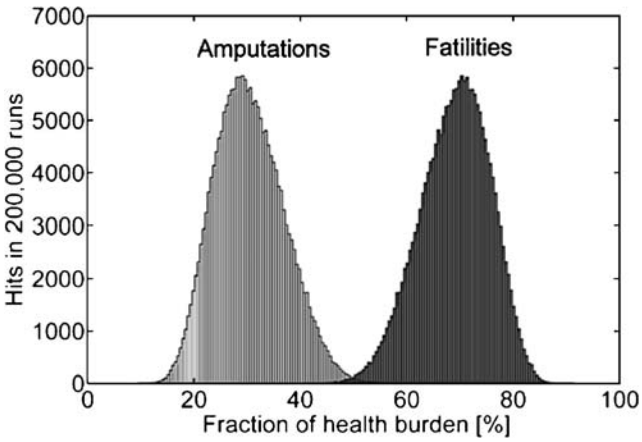

Fig. 2 Distribution of the contribution to health burden from mortality and amputation outcomes

quantifying occupational health impacts in LCIA with DALY using statistical records, it is advised to see if records of lifelong injuries could be used to simplify the effect assessment procedure.

3.3 Health impact per crane lift

A set of 200,000 Monte Carlo runs of Eq. 4 in Table 1 gave an average health damage per crane lift of $4.5 \cdot 10^{-6}$ DALY, with cumulative percentiles $\{P_{2.5}, P_{50}, P_{97.5}\} = \{6.0 \cdot 10^{-7}, 3.1 \cdot 10^{-6}, 1.7 \cdot 10^{-5}\}$. The final distribution is illustrated in Fig. 3. There is significant uncertainty in the result. The 95% confidence interval spans a factor of 5 from the median, corresponding approximately to the variation in the number of injury events per crane lift

The probability of fatal accidents is often used in risk assessment of technical systems. The mean value for crane lifts is $5.6 \cdot 10^{-8}$ fatal accidents per lift, with cumulative percentiles $\{P_{2.5}, P_{50}, P_{97.5}\} = \{7.6 \cdot 10^{-9}, 3.9 \cdot 10^{-8}, 2.0 \cdot 10^{-7}\}$.

The uncertainty in the results compares well to what is found in other methods for quantification of human health impacts in LCIA. For instance, Hertwich et al. (2000) show that parameter uncertainty alone produces a ratio of 10 to 10^3 between the 90th and tenth percentiles in potential doses in human exposure models. Most impact assessment methods show uncertainty in their results by use of σ^2, indicating that a log-normal distribution is assumed. The factor σ^2 in such cases is the factor which, if multiplied or divided by the expected geometric mean, gives the boundaries for the interval of 95% confidence. Huijbregts et al. (2005) indicate a σ^2 of 5 (carcinogenic) and 11 (noncarcinogenic) for human health combined damage and effect factors for toxic substances. Frischknecht et al. (2000) estimate a σ^2 from 15^2 to 65^2 for the human health damage from ionizing emissions depending on substance and emission scenario. Hofstetter (1998) reports σ^2 to be from 15^2 to 50^2 for health damages from the respiratory effect of various inorganic substances. Although these values are reported for different parameters in health damage models in LCIA, and examples of less uncertainty exist, e.g., Müller-Wenk (2004) who indicated an uncertainty in scores for DALY from road noise of a factor of ±2, the 95% confidence intervals in the final characterization factors typically span 1 to 3 units of magnitude.

Sample correlation of the final damage factor and input variables was calculated according to Morgan and Henrion (1990, pp. 208). Results showed a linear contribution of 0.13 from health outcomes in total (DALY per injury event) and −0.98 from the distribution of injury events per unit per year, pointing to the conclusion that the distribution of health burden per accident contributes less to the uncertainty in the result than the distribution of accident frequency.

3.4 Applicability of the factor

Injury event frequency depends on the context in which lift operations are performed. Placing of equipment during operations inherently is a more complex operation than simple loading of containers. Other influencing factors include weather conditions, space limitations on rig and obstructions in the lift zone (which may differ from rig to rig), stress level depending on drilling speed, and technical challenges. This must be kept in mind when using the characterization factor. From the assumptions in the characterization procedure, application of the indicator should be restricted to crane lifts on offshore drilling units, possibly also to mobile rigs.

3.5 Crane lift significance

With the indicator developed for health impacts from crane lifts, it is possible to compare crane lifts with other health

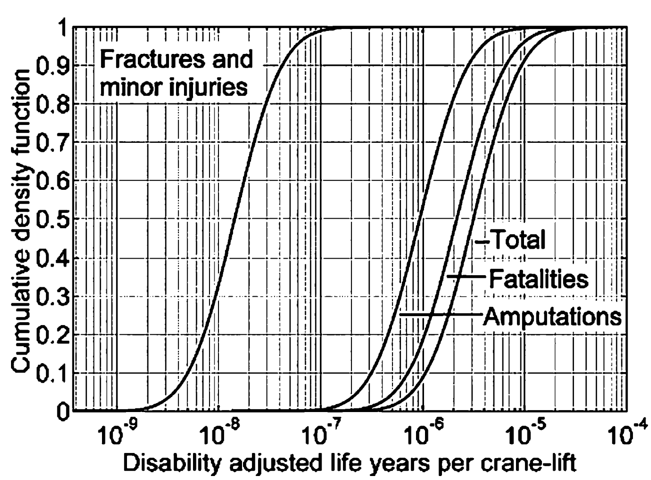

Fig. 3 Health burden per crane lift from recoverable injuries, amputation cases, fatalities and in total

impacts from offshore operations. A valid question is if the characterization factor adds significantly to the assessment of health impacts from offshore operations. Three comparisons were investigated to answer this question, with results summarized in Fig. 4. The following sections describe the calculations for each case, and discuss the significance of results.

3.5.1 Employee safety

In order to compare the significance of the estimated characterization factor with overall industry occupational health, a simplistic LCA reference stream of 1 day of drilling is defined. A mean number of approximately ten lifts per hour in active operations was assumed earlier in this paper, accounting to 240 lifts per 24-h period. With the confidence interval estimated for DALY per lift, the daily burdens from crane lifts account to between 0.00014 and 0.004 DALY.

Average day-rate for JU and SS rigs in UK waters in 1997; the source year for the I/O transactions of Hofstetter and Norris, was US$ 82,200 (ODS-Petrodata 2005). Unfortunately, direct (0th tier) burdens from drilling (BEA sector 110601) are not part of the dataset of Hofstetter and Norris. Petroleum and mineral extraction services (BEA 110602) and engineering, architectural, and surveying services (BEA 730302) are deemed the closest proxy sectors, resulting in daily burdens of 0.074 (mineral extraction) and 0.008 DALY (engineering services) per day. As shown in Fig. 4a), crane lifts seem to constitute a small occupational health burden compared to industry totals for petroleum and mineral extraction and engineering services.

3.5.2 End-of-life contribution

The Barents Sea was recently opened for petroleum drilling under requirements that drilling chemicals are not discharged to the sea. Reinjection of the rock phase carved from the well (i.e., cuttings) and chemical residues on cuttings to subsea formations, a common solution in the North Sea, is not an option in the Barents Sea area due to lack of a dedicated well and suitable formations for injection to same well. The drilling waste must, therefore, be brought to shore for treatment.

Approximately 1,000 metric tons of cuttings with residues is produced per well. In the intermediate storage and transportation to an onshore treatment facility, this represents approximately 11 lifts of 220 containers, each holding 4.5 metric tons of drilling waste. The cuttings transport chain to shore further involves:

1) Ship transport in two stages with total fuel use of 66 l low-s diesel: rig–onshore supply base (supply vessel)–treatment facility port (container vessel)
2) Truck transport: port–treatment facility (10 km road transport to facility, empty on return)

Complete inventories for the transport chain are presented by Pettersen (2007). The Eco-indicator 99 method (Hierarchist, Goedkoop and Spriensma 2002) is used in impact assessment as it offers health impacts in DALY. The following adjustments were made to accommodate local conditions and the offshore situation (1) health impacts from radiation, ozone layer depletion and climate change were excluded, (2) fate factors for respiratory effects from direct ship emissions were reduced by a factor of 2 to adjust for the offshore situation, and (3) damage factors for direct

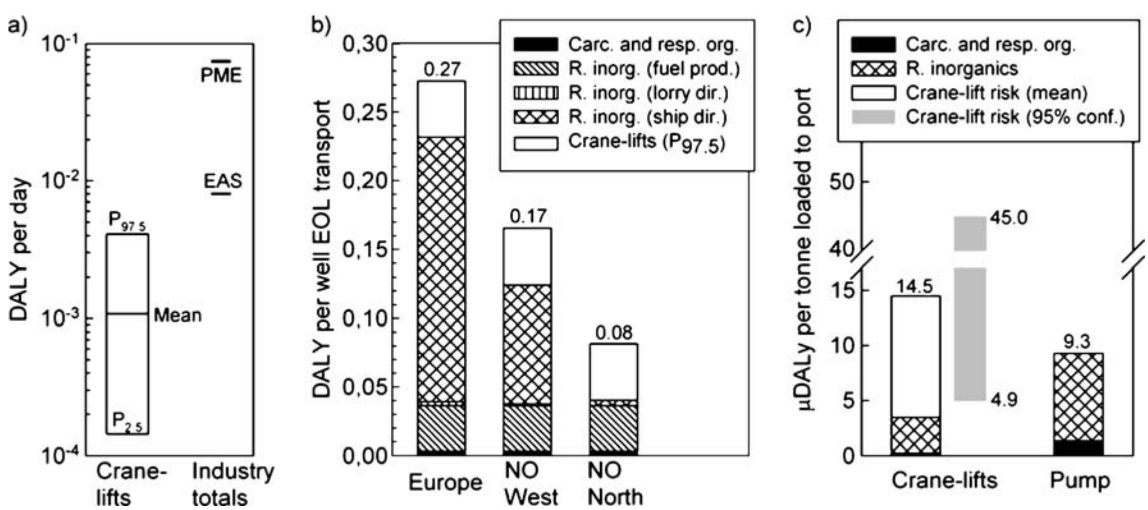

Fig. 4 The health significance of crane lifts to **a** overall industry health impacts, **b** end-of-life transport chain for drilling waste, and **c** selection of loading technology. *PME* = petroleum and mineral extraction, *EAS* = engineering, architecture and surveying, *Carc.* = carcinogenics, *R* = respiratory, *inorg.* = inorganics, *org.* = organics, *dir.* = direct emissions, *NO* = Norway

emissions were adjusted according to regional population densities; Europe (80 cap. per km^2), West Norway (NO West, 36 cap. per km^2), North Norway (NO North, 1.6 cap. per km^2). Human health impacts from the transport chain are illustrated in Fig. 4b. Depending on location, the results show that crane lifts constitute a significant—or possibly even dominant—portion of the health impacts from the end-of-life transport chain for drilling wastes.

3.5.3 Loading technology comparison

Reduction in health impacts from crane lifts can be achieved by using other means of loading cargo off and aboard ship. A hydraulic system (i.e., pump system) was recently installed on a drilling rig for loading cuttings off rig onto supply vessels, and off vessel at port. Although not included in this evaluation, a second benefit of the hydraulic system is that it is a closed system. It, thereby, reduces occupational exposure to particulates and chemicals. We report here on the comparison of life cycle health impact from the pump system compared to the continued use of cranes, based on a functional unit of 1 metric ton of cuttings loaded off rig to supply ship, and off ship onto port at shore. Complete inventories are reported by Pettersen (2007). All current rigs are pre-equipped with cranes. Production was therefore only included for the pump system. The Eco-indicator 99 method (Goedkoop and Spriensma 2002) was used to characterize health impacts from emissions, applying the same modifications as described in the previous section for the European situation.

Results are presented in Fig. 4c. For the crane lift alternative we find that health impacts are dominated by crane accidents. Moreover, the expected health impacts from crane lift accidents shifts the relative comparison of the two alternatives in favor of the pump system. Uncertainty analysis including uncertainty in health impacts from respiratory inorganic emissions and crane lift risk supports the pump system as the best alternative in terms of health impacts by 87% of outcomes in Monte Carlo simulation (Pettersen 2007).

4 Conclusions

Accident records were used to develop an empirical characterization factor for offshore crane lifts. The mean health damage is $4.5\cdot10^{-6}$ DALY per crane lift, with cumulative percentiles $\{P_{2.5};\ P_{50};\ P_{97.5}\}=\{6.0\cdot10^{-7},\ 3.1\cdot10^{-6},\ 1.7\cdot10^{-5}\}$. Although uncertainty related to the characterization factor is significant, it is less than what is indicated for other human health impact chains currently included in LCA. The spread in the result is not only mainly caused by the random nature of accidents (variability) but is also attributed to the estimation procedure (parameter uncertainty).

Recoverable injuries were found to be of little significance to the DALY from crane lift accidents. Fatality cases dominated the health burden, representative of 70% of the total.

Applications presented in this paper show that crane lifts may be significant, or even dominant, to the life cycle performance of offshore drilling technologies with respect to human health impacts. These are valuable insights to the overall evaluation of offshore drilling fluid technology, and the characterization factor for crane lifts will be used in future case studies.

5 Perspectives on occupational health in LCA

The characterization factor for crane lifts allows the identification and evaluation of life cycle health impacts that otherwise would have been overlooked in LCA of loading systems and other drilling fluid technologies. In our view, the integration of occupational health into the assessment adds value to LCA as decision support. However, this is a perspective not shared by all members of the LCA community. In the peer review process for this paper, several points were made by the reviewers against allowing occupational health issues to be modeled within the framework of LCA. This section contains a summary of the arguments exchanged between the reviewers and authors during the review process.

One reviewer stated that there is a divide between occupational issues and LCA and that these should be handled by use of separate tools. Comprehensiveness is generally forwarded as a major strongpoint of LCA. As long as we are able to treat occupational issues within LCA, we find this separation arbitrary. The process outlined in this paper is aimed at investigation of tradeoffs made between health impact caused by occupational hazard and emissions made to the environment. In the terminology of Wrisberg et al. (2002), this is the overlapping of tools for assessment of occupational safety and life cycle environmental impact.

Advocates against inclusion of occupational accidents in LCA make two main claims. The first is that the workforce is not part of the environment (that we conventionally consider), and the second is that accidents are unintended incidents which, in any case, may be omitted by proper operational control. It is our opinion that both these arguments are flawed.

According to the formalized LCA framework, the term environment describes the surroundings in which an organization operates, including human as well as natural and biological resources (ISO 2006; Udo de Haes and Lindeijer 2002). Some interpret the workforce as part of the

organization itself rather than as part of the environment. Life cycle assessment may then be said to be concerned with impacts caused by product systems upon the outside world. While this separation is advocated by the reviewers, we find this an artificial exclusion of environmentally relevant impacts for which mechanisms in principle are the same or endpoint consequences are shared by occupational accidents and the so-called conventional impacts. Meijer et al. (2005) show an example of expanding the definition of the environment, in their case to consider indoor exposure from building materials. The results show that human health impacts are traditionally underestimated in LCA unless indoor pollution is integrated into the assessment—indoor release being an issue otherwise left to be handled solely by building standards. Hazardous operations leading to occupational accidents with consequences to human health are an example of the second class of artificially excluded impacts. The endpoint consequence is the same as for emission-related health effects—the loss of human health. Omitting occupational health from the assessment potentially overlooks important health damages, thereby allowing problem shifts to pass unidentified.

The second claim made against modeling occupational health with LCA is that accidents are unintended and, as such, should not be included. However, the concept of probability is integral to LCA, particularly in the assessment of human health impacts. Hence, occupational accidents should be included in the assessment as long as we are able to establish, and with relative certainty also model, the cause–consequence chain. If we replace the term "accident" with "probability of consequence," we see that the conventional exposure models and statistical analysis share many features. All exposure models are based on a best approximation of the real world, and uncertainty in the environmental fate of substances is frequently assessed by Monte Carlo simulation. Resulting exposures, thereby, are in the form of probability distributions (Hertwich et al. 2000), with model parameters established from empirical observations. Statistical analysis and probabilistic modeling also forms the basis for human-toxic effect factors, apparent for instance in the results of Huijbregts et al. (2005) and Hofstetter (1998). In the end, category indicators for the so-called conventional impact chains are produced with factors that have a significant uncertainty due to model assumption, parameter uncertainty, and response variation. This work has shown that an empirically based characterization factor for accidental outcomes may compare well to emission-related impact chains in terms of uncertainty.

Finally, a strong argument for the inclusion of occupational issues is that it adds value to LCA. The updated ISO standard for LCA allows great flexibility on the part of the practitioner to design the LCA study according to stated goals and scope. Inventories may, thereby, contain information on other environmental aspects, while life cycle impact assessment is the process of understanding the significance of all inventory items (ISO 2006). Within these bounds, we should find room also for occupational health damages. We must be careful not to let LCA become obsolete by excluding new or nonconventional developments merely because they are novel. One of the lessons learned in the history of LCA is that there is no "correct" set of impact categories in LCA (Barnthouse et al. 1997). Moreover, the life cycle community may find normative sources also outside the ISO framework. An example of an additional source of policy relevance of LCA is the European Union Directive for integrated pollution prevention and control, which asks for the simultaneous consideration of accidents, emissions and resource issues (EC 1996). The directive has led to a large body of LCA-like reference documents aimed at the establishment of best available techniques for various sectors.

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